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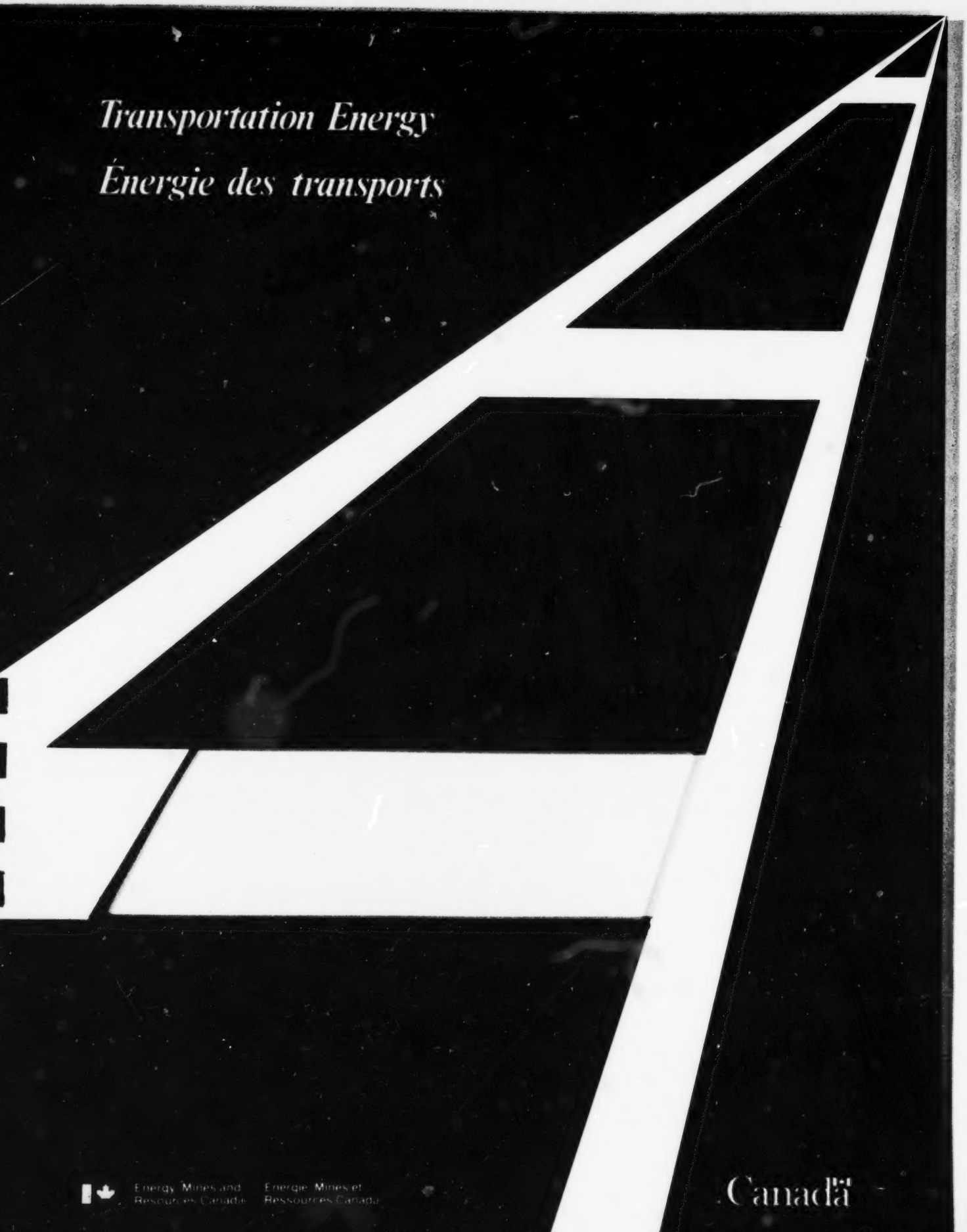

Energy, Mines and Resources Canada
Énergie, Mines et Ressources Canada

Canada

# Investigation of Methodologies, Technical Innovations and Development Requirements

## Phase 1 - Feasibility Analysis

## DUAL FUEL NATURAL GAS/DIESEL CONVERSION SYSTEM IN FOUR-STROKE DIESEL ENGINES

TE-84-13

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and
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January 1985

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Etude des méthodologies,
des innovations techniques et
des perfectionnements nécessaires

Phase 1 - Etude de faisabilité

# DISPOSITIF D'ALIMENTATION DES MOTEURS DIESELS A QUATRE TEMPS EN GAZ NATUREL-DIESEL

TE-84-13

Rapport établi par:
IBI Group
et
B.C. Research
Janvier 1985

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TABLE OF CONTENTS


| | | Page |
|---|---|---|
| 1.0 | INTRODUCTION. . . . . | 1 |
| 2.0 | CONVERSION POTENTIAL - FOUR-STROKE DIESEL TRUCKS . . . . . | 2 |
| | 2.1 Introduction . . . . . | 2 |
| | 2.2 Number of Potential Trucks for Conversion. . . . . | 3 |
| | 2.2.1 Number of trucks. . . . . | 3 |
| | 2.2.2 The geographical distribution . . . . . | 4 |
| | 2.2.3 Engine and vehicle type . . . . . | 5 |
| | 2.2.4 Annual metrage. . . . . | 7 |
| | 2.2.5 Urban and inter-city shares . . . . . | 9 |
| | 2.2.6 Target markets. . . . . | 11 |
| 3.0 | THE INITIAL CANADIAN MARKET . . . . . | 15 |
| 4.0 | EXTENSION TO OTHER MARKETS. . . . . | 16 |
| 5.0 | LITERATURE REVIEW . . . . . | 17 |
| | 5.1 Introduction . . . . . | 17 |
| | 5.2 Background . . . . . | 18 |
| | 5.3 Problem Areas for Dual-Fuel Diesel Engines . . . . . | 19 |
| | 5.4 Existing Dual-Fuel NGV Conversion Systems. . . . . | 20 |
| | 5.5 NGV/Diesel Conversion in New Zealand . . . . . | 21 |
| 6.0 | CONTROL SYSTEM STRATEGY FOR A SECOND GENERATION DUAL-FUEL CONVERSION SYSTEM . . . . . | 23 |

TABLE OF CONTENTS

(continued)


| | | Page |
|---|---|---|
| 7.0 | RECOMMENDATIONS FOR THE DEVELOPMENT OF A MODERN DUAL-FUEL CONVERSION SYSTEM . . . . . | 25 |
| 8.0 | CONCLUSIONS . . . . . | 26 |
| 9.0 | REFERENCES. . . . . | 27 |

# DISPOSITIF D'ALIMENTATION DES MOTEURS DIESELS À QUATRE TEMPS EN GAZ NATUREL-DIESEL

## 1.0 INTRODUCTION

Il serait possible de réduire considérablement la consommation de carburant diesel au Canada si l'on convertissait suffisamment de camions au diesel pour leur permettre de consommer principalement du gaz naturel, en reléguant le diesel au rang de carburant-pilote. Même s'il a été démontré qu'il est techniquement possible de faire fonctionner des moteurs diesels au moyen de mélanges contenant jusqu'à 90 % de gaz naturel, il n'existe pas encore sur le marché un dispositif d'alimentation moderne qui conviendrait aux moteurs diesels des camions couramment utilisés.

Cette étude a donc pour buts de créer un dispositif d'alimentation en gaz naturel-diesel, prototype de la "deuxième génération", capable de fournir un rendement satisfaisant sur des camions lourds commerciaux, puis d'en vérifier le fonctionnement en laboratoire. Étant donné que ce système de commande doit pouvoir être fabriqué commercialement, la première phase de notre étude vise à évaluer le marché de ce type de dispositif et à examiner l'état actuel de la technologie en ce qui concerne surtout les moteurs diesels à quatre temps (des travaux se font parallèlement sur les moteurs à deux temps). Le présent rapport, qui rend compte des résultats de cette première phase de notre étude, renferme trois parties principales:

- examen de certains marchés cibles au Canada, avec estimation du nombre de véhicules convertibles, de leur consommation de carburant et des taux de conversion réalisables;

- examen de la technologie de la conversion des moteurs diesels, en particulier les moteurs à quatre temps qui équipent les poids lourds commerciaux;

- évaluation des possibilités de commercialisation d'un dispositif de conversion fabriqué en série.

Les auteurs concluent qu'il existe au Canada un marché pour des dispositifs de conversion de la "deuxième génération", et que les travaux de développement à exécuter dans le cadre de ce projet pourraient contribuer d'une large façon à implanter commercialement l'utilisation du gaz naturel dans les moteurs conçus pour fonctionner au diesel.

# DUAL FUEL NATURAL GAS/DIESEL CONVERSION SYSTEM IN FOUR-STROKE DIESEL ENGINES

## 1.0 INTRODUCTION

Significant reductions in Canada's consumption of diesel fuel may be possible if substantial numbers of diesel powered trucks can be converted to use natural gas as their major fuel, with diesel serving as a pilot fuel only. While the operation of diesel-cycle engines on mixtures of up to 90% natural gas has been shown to be technically possible, modern conversion equipment is not yet commercially available for commonly used truck diesel engines.

The objective of this project is to develop a prototype "second generation" natural gas/diesel conversion system that will produce satisfactory performance when installed in commercial heavy trucks, and to test it under laboratory conditions. It is intended that this control system will eventually be manufactured commercially; thus the first phase of this project assesses the market for the system and reviews the technical state of the art with particular reference to four-stroke diesels (a parallel project deals with two-stroke diesels). This Phase 1 report contains three major sections:

- a review of some Canadian target markets, with estimates of the numbers of eligible vehicles, their fuel consumption, and the rate of conversion that might be achieved;

- a review of diesel engine conversion technology, with particular reference to four-stroke commercial heavy truck engines;

- an assessment of the market potential for a commercially manufactured conversion system.

This report concludes that a market is available in Canada for such a "second generation" conversion, and that the development work to be carried out under this project can make a significant contribution to the commercial adoption of natural gas as an alternative fuel in diesel engines.

## 2.0 CONVERSION POTENTIAL - FOUR-STROKE DIESEL TRUCKS

### 2.1 Introduction

This section of the report specifically identifies some groups of diesel powered heavy trucks that might find conversion to natural gas economically attractive and technically feasible; in addition the number of trucks involved in each group has been calculated. The basis of this calculation and the assumptions made, are presented in the text; the results are summarized in Table I - page 10.

No attempt has been made to conduct a complete survey of all eligible vehicles in Canada; rather, the approach taken is to examine in some detail the truck populations of two most likely market areas, and to determine whether these markets alone might justify the cost of development of a suitable natural gas/diesel control system.

Road Motor Vehicles in Canada consume approximately 5,300 million litres of diesel fuel a year (Statistics Canada 53-218 for 1981). However, some of this fuel is used in areas where natural gas is not available; some is used in vehicles whose characteristic duty cycles do not lend themselves to natural gas conversion. To narrow the range to identify initial markets where conversion of diesel engines to

natural gas operation may be economic and feasible, this study has concentrated on Ontario and British Columbia. In these provinces, fleets in the Toronto-Hamilton-London area and in the Lower Mainland may offer sufficient concentration to permit an infrastructure and marketing program to be developed, to encourage conversion. Ontario and British Columbia between them, account for 2.7 billion litres of diesel fuel consumption a year, or almost exactly 50% of the national consumption of diesel fuel for road transport purposes, as follows:

| | |
|---|---|
| Ontario | $1986 \times 10^6$ litres |
| B.C. | $668 \times 10^6$ litres |
| Rest of Canada | $2616 \times 10^6$ litres. |

In the section that follows, data are presented to estimate:

- the number of trucks
- their geographical distribution
- engine type
- the annual metrage
- the relative urban and intercity shares.

## 2.2 Number of Potential Trucks for Conversion

### 2.2.1 Number of trucks

The number of registered trucks over 10,000 kg ("heavy" trucks) is:

| | | |
|---|---|---|
| Ontario | 143,353 | - MTC Ontario 1982 |
| B.C. | 28,916 | - Dept. of Highways B.C. 1983 |
| Total | 172,269 | |

2.2.2 The geographical distribution

In Ontario, 81% of the heavy truck registrations are in the Sarnia, London, Hamilton, Toronto or Ottawa regions, in most parts of which there is sufficient density of traffic for a natural gas supply to be available if desired. The remainder are registered in the Sault Ste. Marie or Thunder Bay regions, where it is less likely that the demand could be sufficiently concentrated to warrant installation of compressors and conversion facilities.

In Ontario, it is assumed that about 75% of the demand is sufficiently concentrated to be serviceable. In British Columbia, the main area of concentration is the Lower Mainland, with a possibility for trucks in other communities such as Kamloops (where there is a public NGV refuelling station) or Prince George. Vancouver Island at this time is not served by natural gas.

Data obtained from the Insurance Corporation of British Columbia shows a total of 11,067 trucks of over 15,500 kg in the Lower Mainland in 1982, compared with 17,714 in the Province as a whole, i.e. in this class, which is a major component of the road diesel use, 62% of the vehicles are in the Lower Mainland. Moreover, a study for B.C. Hydro (Canadian Resourcecon 1983) estimates Lower Mainland diesel fuel consumption for road purposes as 410 million litres, which is 62% of the estimated annual consumption, for road purposes, of 668 million litres.

Assuming that the 62% of the heavy trucks in the Lower Mainland are readily serviceable with natural gas and making an allowance for some opportunity in Kamloops and Prince George, it is estimated that approximately 70% of British Columbia's heavy trucks demand could be serviced by natural gas.

Using these ratios, the number of heavy diesel trucks in the serviceable parts of each Province are estimated as:

| | | |
|---|---|---|
| Ontario | 75% of 78,800 | = 59,100 |
| B.C. | 70% of 15,900 | = 11,100 |
| Total | | 70,200 |

2.2.3 Engine and vehicle type

Engine manufacturers estimate that about 75% of diesel trucks over 15,500 kg and 90% of diesel trucks between 10,000 and 15,500 kg are equipped with four-stroke engines. This correponds to about 84% of all heavy trucks and leads to estimates of heavy four-stroke diesel trucks in the serviceable parts of each province as:

| | |
|---|---|
| Ontario | 49,800 |
| B.C. | 9,300 |
| | 59,100 |

Based on sales of new trucks with four-stroke engines, the market shares of new engines by manufacturer are estimated as:

| | |
|---|---|
| Cummins | 45% |
| Caterpillar | 30% |
| Mack | 10% |
| International Harvester | 10% |
| Other | 5% |

However, as shown below, the Caterpillar share of the existing (and potential retrofit) market is higher.

Heavy trucks are commonly subdivided into three subsets defined by their gross vehicle weight as follows:

| | | |
|---|---|---|
| Group 6 | 8,845 - 11,794 kg | (19,501 - 26,000 lbs) |
| Group 7 | 11,795 - 14,968 kg | (26,001 - 33,000 lbs) |
| Group 8 | 14,968 kg & over | (33,001 lbs and over) |

The majority of Group 6 and 7 vehicles are powered by diesel engines while all Group 8 vehicles are diesel powered. Group 6 and 7 vehicles typically have diesel engines from 112 - 187 KW (150 - 250 HP) and Group 8 trucks use engines with power ratings greater than 187 KW. During the period from 1970 - 1982 approximately 68% of all new Group 6 and 7 trucks sold were powered by the Caterpillar 3208 V-8 engine. Since 1980 the International Harvester Model IH 466 and General Motors 8.2 litre diesel engine have increasingly been used in Group 6 and 7 vehicles. However the Caterpillar 3208 still powers 50% of existing Group 6 and 7 trucks (Carthy 1984).

Group 8 trucks (inter-city) predominantly use either Caterpillar or Cummins diesel engines. As an example of the distribution of engines used in Group 8 vehicles Freightliner's engine utilization (Pope (1984)) in their heavy long haul trucks is given below:

| Engine Manufacturer | % of Engines Used |
|---|---|
| Detroit Diesel Allison | 4 |
| Caterpillar | 48 |
| Cummins | 48 |

Approximately 95% of the Caterpillar engines used are the Model 3406 while a similar fraction of the Cummins engines used are the Model NTC 400. The remaining Cummins engines used include NTC 350, NTC 475, Big Cam 400 and Formula 400.

It thus appears that Caterpillar accounts for about 50% of the existing diesel truck engines in Group 6, 7 and 8.

2.2.4 Annual metrage

The average annual metrage of heavy trucks in Canada is estimated as 41,000 km; and of medium trucks (5,001 - 10,000 kg) 24,000 km (Transport Canada 1979). Almost no published information is available on the range of annual or daily metrage, but information is available in the U.S. Census of Transportation (1977). This shows that for groups 7 and 8 trucks (over 26,000 lbs or 11,794 kg) and for group 6 trucks (19,501 - 26,000 lbs or 8,845 - 11,794 kg) the distributions of annual metrages are as follows:

| | Groups 7 & 8 % of Trucks | Group 6 % of Trucks |
|---|---|---|
| less than 8,000 km | 17.5% | 41.4% |
| 8,000 - | 12.6% | 21.0% |
| 16,000 - | 18.7% | 22.0% |
| 32,000 - | 11.0% | 8.3% |
| 48,000 - | 12.9% | 5.3% |
| 80,000 - | 11.6% | 1.5% |
| 120,000 and up | 15.8% | 0.5% |
| Mean | 56,000 km | 16,000 km |

It is likely that the 30% of the groups 7 and 8 trucks and the 62% of the group 6 trucks, which travel less than 16,000 km a year, are primarily the gasoline-powered vehicles in the fleet. For such annual distances it would not be economic to invest the additional money involved in a diesel vehicle.

If only 10% of the diesel trucks in each class travel less than 16,000 km a year, with the balance having a pattern as shown for over 16,000 km in the above table, the average metrage of groups 7 and 8 diesel trucks would be 68,000 km and for a group 6 truck 35,000 km.

Truck fuel consumptions have been estimated in reports as follows:

| Source (see references) | Weight of truck (kg-GVW) | Year of Study | Fuel Consumption (l/100 km) |
|---|---|---|---|
| Transportation Energy Management Program (1982/83) | For hire | 1980 | 59.8 |
| Middleton/Mueller (82) | 10,000 | 1979 | 51.4 |
| Energy, Mines and Resources (1982) | 9,000 | 1979 | 57.2 |
| Canadian Resourcecon (1976) | 15,000 | 1976 | 57.4 |

It is believed from discussions with trucking company managers that there have been increases in fuel efficiency with the increase in fuel prices. Hence we have assumed a value of 52 litres per 100 km for trucks in Classes 6, 7 and 8. This leads to estimates of annual fuel consumption of 35,400 litres for Class 7 and 8 diesel trucks and 18,200 litres for Class 6 diesel trucks.

However, these estimates are based on metrages derived from 1977 United States data. Since that time, general automotive annual metrages have gone down, although there is no specific evidence for truck metrages. An adjustment to 30,000 litres

per year for trucks over 15,500 kg, and 15,000 litres for those between 10,000 and 15,500 kg (yielding an overall average of 21,000 litres for heavy trucks) would appear to be consistent with present Canadian experience.

Applying the estimate of 21,000 litres/year to the number of trucks reported in Section 2.2.3 on page 5 leads to estimates of annual fuel consumption of heavy four-stroke diesel engine-powered trucks in the serviceable areas of Ontario and B.C. as:

| | | |
|---|---|---|
| Ontario | 1,050 | x $10^6$ litres |
| B.C. | 200 | x $10^6$ litres |
| | 1,250 | x $10^6$ litres |

2.2.5 Urban and inter-city shares

The pattern of truck usage varies considerably from region to region. In Southern Ontario with a network of cities, much of the travel may be inter-city with a smaller proportion of urban use. In British Columbia, with a concentrated single metropolitan area in the Lower Mainland and a more sparsely inhabited hinterland, a greater percentage of urban travel can be expected within Greater Vancouver and a smaller amount of inter-city use.

Two available studies confirm the expected patterns of fuel consumption for heavy trucks as follows:

| | Lower Mainland B.C. Canadian ResourceCon - 1983 | Ontario IBI - 1983 |
|---|---|---|
| Inter-City Use | 32% | 66% |
| Urban Use | 68% | 34% |

TABLE I

Summary of Calculation - Eligible Trucks and Their Fuel Consumption

| | Ontario | B.C. |
|---|---|---|
| Total number of heavy trucks | 143,000 | 29,000 |
| Percentage diesel powered | 55% | 55% |
| Total diesel powered | 79,000 | 16,000 |
| Percentage in target area | 75% | 70% |
| Total diesel heavy trucks in target area | 59,000 | 11,000 |
| Percentage four-stroke | 84% | 84% |
| Total four-stroke diesel heavy trucks in target area | 50,000 | 9,200 |
| Percentage Caterpillar powered | 50% | 50% |
| Number of Caterpillar powered diesel trucks eligible | 25,000 | 4,600 |
| Average annual metrage (km) | 42,000 | 42,000 |
| Average diesel consumption (litres) | 21,000 | 21,000 |
| Total annual diesel fuel consumed by eligible four-stroke diesel trucks (millions of litres) | 1,050 | 200 |
| Inter-city use | 690 | 65 |
| Urban use | 360 | 35 |
| Percentage of eligible trucks that could feasibly be converted | 50% | 50% |
| Number of four-stroke Caterpillar conversions each year (@ 1% per year) | 125 | 25 |
| Diesel consumption replaced by Natural Gas consumption (per year) after ten years of Caterpillar conversions (millions of litres) | 20 | 4 |
| Equivalent dollar savings at 20 cents per litre ($ millions) | 5 | 1 |

A strategy of conversion for B.C. may therefore differ from one for Southern Ontario.

The above values, applied to the fuel consumption of four-stroke diesel engines in serviceable areas, would yield estimates (in millions of litres per year) of:

| | B.C. | Ontario |
|---|---|---|
| Inter City Use | 65 | 690 |
| Urban Use | 135 | 360 |
| Total | 200 | 1,050 |

Approximately 10-20% of this fuel might continue to be needed as a pilot fuel, with the balance available for replacement by natural gas depending on the proportion of vehicles converting.

2.2.6 Target markets

There are many factors which will affect whether a truck can convert to natural gas. These will include:

- the fuelling pattern
- the conversion cost
- the physical ability to install the necessary cylinders.

The paragraphs below discuss these factors and their implications before assessing the market.

Fuelling pattern

For inter-city travel, a typical highway tractor is estimated to carry 900 litres of diesel with some adding tanks to bring the capacity to 1,500 litres.

In British Columbia, a typical journey to Alberta would involve a distance of 1,000 km, requiring 500 litres of fuel. A round trip to Seattle would be 500 km. In Ontario, the stage lengths of Toronto-Windsor, Hamilton-London, etc. would be shorter than the British Columbia pattern.

Drivers of the inter-city trucks take rest stops, perhaps every 350 km (or 175 litres of fuel utilization). More frequent stops for fuelling would be possible, but the time and inconvenience would probably discourage conversion. It is suggested that enough cylinders should be carried to provide this minimum range, if possible.

For urban use, the trucks would normally return to home base each night. If 15,000 litres a year is an average consumption of a 10,000 - 15,000 kg truck, and 30,000 litres a year is typical of trucks over 15,500 kg, then for a 250 working day year, these figures imply daily consumptions of 60 and 120 litres respectively. It would clearly be desirable to carry at least the natural gas equivalent of these daily volumes.

Conversion cost

A 66-litre lightweight steel cylinder weighs 54 kg and costs approximately $400. It contains the equivalent of about 17.5 litres of fuel. If in operation the NGV is used in conjunction with diesel fuel in an 80:20 proportion, then one such cylinder in conjunction with pilot diesel fuel will provide the equivalent of 21.9 litres of diesel.

Hence, the desirable number of cylinders will be:

| | Equivalent Litres of Diesel Fuel | Number of Cylinders |
|---|---|---|
| Inter-city | 175 | 8 |
| Typical Urban 15,500 kg+ | 120 | 6 |
| Typical Urban 10,000 - 15,500 kg | 60 | 3 |

In addition to the cylinder cost, it will be necessary to install the conversion equipment (estimated at $2,000 materials and $1,000 labour). This leads to costs per conversion of:

| | |
|---|---|
| Inter-city | $6,200 |
| Typical Urban 15,500 kg+ | $5,400 |
| Typical Urban 10,000 - 15,500 kg | $4,200 |

Natural gas is typically sold at a price of 23¢/litre on an energy equivalent basis. Diesel fuel retails for 45-50¢/litre depending on location. Hence a reasonable estimate of the savings per litre of diesel fuel replaced by a natural gas/diesel supply would be 20¢ per litre, and if a repayment time of 3 years is assumed, then the annual metrages to justify these expenditures (assuming 50 litres per 100 km) would be:

| | |
|---|---|
| Inter-city | 20,700 km |
| Typical Urban 15,500 kg+ | 18,000 km |
| Typical Urban 10,000 - 15,500 kg | 14,000 km |

These metrages would appear likely to be exceeded by most diesel trucks in the respective services. However, some trucks serving many markets (e.g. both B.C. - California and B.C. - Alberta) might not travel an adequate metrage within the area potentially served by natural gas.

Physical feasibility

The mass of the natural gas will approximately equal that of the diesel fuel which it replaces. However, the cylinders will have a mass of 200 kg to 500 kg depending on the number installed. The additional weight may present an unacceptable penalty to some trucks. Other vehicles will "cube out", reaching the maximum volume of the vehicle, so that weight is not a problem. However, many vehicles are designed to occupy the maximum permitted dimensions and to bring the trailer (if any) as close as possible to the tractor. This may make it difficult to find space to locate the cylinders. Yet other vehicles may neither "weight out" nor "cube out" but may have a special purpose design, such as dump trucks or garbage-compactor trucks, which will make cylinder location difficult.

There is no hard information on which to base an estimate of the number of trucks to which it is physically feasible to attach cylinders. However, it would appear likely that the greatest opportunity lies in the urban or short-haul inter-city trucks. It seems likely from discussions with some operators that the long-haul inter-city trucks are more generally vehicles which are designed to carry either maximum weight or to use fully any dimensional limits allowed to them. This, combined with the requirement to carry more cylinders, because of the distance between refills, means that the inter-city vehicles would be less likely to be able to carry the cylinder weight or to find space for them.

With urban or short-haul vehicles, however, there is more opportunity to refill, and weight and space are not so crucial. An attempt to locate 3 to 6 cylinders will be easier than trying to find space for 8. Moreover, in addition to the opportunity to convert diesel engines, there could be the opportunity to convert some of the higher annual metrage gasoline engines to natural gas, thus permitting a broader marketing thrust at these vehicles as a class.

## 3.0 THE INITIAL CANADIAN MARKET

The initial Canadian target market is therefore recommended as that of urban and short-haul inter-city trucks in Southern Ontario and the Lower Mainland of British Columbia which are presently powered by Caterpillar engines (excluding such vehicles as dump trucks, ready-mix concrete trucks or garbage-compactors where weight or design renders cylinder attachment difficult).

Very broadly, this initial target market might account for about half of the total heavy truck fleet in these geographical regions powered by Caterpillar four-stroke diesel engines, since it will consist of:

- many of Ontario's urban vehicles (34%) plus a proportion of their inter-city vehicles (66%)

- many of B.C.'s urban vehicles (68%) plus very few of their inter-city vehicles (32%).

Since Caterpillar is estimated to power half of the relevant engines, the trucks which are both urban and Caterpillar-powered may account for approximately 25% of the

heavy truck fleet in the target areas. If an attempt is made to convert 1% of these vehicles a year for 10 years, this would lead to the following estimate of annual conversions of trucks with Caterpillar engines:

| | Truck Conversions (per year) | Annual Diesel Fuel Replaced by Natural Gas/Diesel Mix (millions of litres) | Arnual Saving at 20¢ per Litre Cost Differential ($ millions) |
|---|---|---|---|
| Ontario | 125 | 2.5 | 0.5 |
| B.C. | 25 | 0.5 | 0.1 |
| Total | 150 | 3.0 | 0.6 |

The annual conversions would cost about $750,000 and pay for themselves in 18 montns. By the end of ten years on this basis, about 30 million litres of diesel fuel would be replaced by a natural gas/diesel mix, saving $6 million per year.

## 4.0 EXTENSION TO OTHER MARKETS

Beyond the initial market, there is the potential to extend the technology to other engines and to extend the geographical area of application to the rest of B.C. and Ontario and to other provinces, as and when natural gas becomes available and NGV is more plentifully supplied.

A major potential would exist for sales of conversion kits in the United States if the relative economics of natural gas and diesel were attractive. At the present time this is not generally so, but given the political nature of fuel pricing this situation could change.

There is also the potential for exporting conversion kits to other parts of the world where the natural gas/diesel price differential is attractive.

Finally, within Canada there is major savings potential with the conversion of larger diesel engines, such as those used in mining trucks, ferries and other large prime movers. At the present time, Canada is dependent on overseas engine manufacturers to make these conversions. It is possible that the work on the conversion technology for smaller engine sizes will develop skills which would enable Canada to make a contribution to such conversions.

## 5.0 LITERATURE REVIEW

### 5.1 Introduction

A computer literature search was conducted to determine relevant information on the use of natural gas to fuel diesel engines used in heavy trucks. The data bases included in this search are given below:

- NTIS (National Technical Information Service) Data Base, 1964-84.
- Engineering Index, Data Base, 1970-84.
- Society of Automotive Engineers Data Base, 1965-84.
- TRIS (Transportation Research Information Service), 1970-84.
- Canadian Transportation Documentation System, 1960-84.
- Chemical Abstracts, 1973-84.
- PROMPT, 1972-84.

The computer search provided more than 250 references of which approximately 45 were relevant. The key findings of the literature review are summarized below.

## 5.2 Background

Today there are numerous stationary dual-fuel diesel engines in service operating on natural gas. These engines are generally used to power pumps, compressors and electrical generators, and such engines have been used commercially for nearly fifty years (Boyer (1949)).

Stationary dual-fuel engines generally operate under fixed speed and load conditions. This type of service allows a very elementary engine control system to be used which allows the engine operating conditions to be optimized to achieve very high efficiencies (Land (1967)).

While stationary dual fuel diesel engines have been used extensively, there are very few transportation applications (eg. heavy trucks) for this type of engine (Karim (1982)). There are two reasons for this, one economic and the other technical. The most important reason is that until recently diesel fuel has been relatively inexpensive and there was not economic incentive to consider alternative fuels. This is not the case today. The other reason is that for transportation applications the engine control system is rather complicated and must be able to accommodate a wide range of engine speed and load conditions (U.S. DOE (1980)). Currently there are a number of commercially available dual-fuel NGV conversion systems. Although these systems work, they do not optimize the operation of the engine, either in overall efficiency or in the amount of diesel fuel replaced. For dual-fuel NGV engines to be a viable alternative, considerable development work is required for engine control systems. In general the control system will have to be matched to the characteristics of the engine to be converted.

## 5.3 Problem Areas for Dual-Fuel Diesel Engines

There are three problems that must be addressed before dual-fuel diesel engines can be harnessed efficiently to power heavy trucks (primarily four stroke engines) (Karim (1980), Karim (1982) and O'Neal (1982)).

The first problem is that under partial load conditions the efficiency of a natural gas (or any gaseous fuel) dual-fuel engine using diesel fuel pilot injection is lower than for a diesel engine (Karim (1967), Moore (1955), and Karim (1968)). This is due to the difficulty of igniting the natural gas/air mixture. To improve the efficiency at light loads, more diesel pilot fuel must be added. At high loads the efficiency of a natural gas dual-fuel engine is higher than for straight diesel operation (Karim & Singh (1967), Karim & Khan (1968)). For heavy load operation, less pilot fuel can be used. Hence, to maximize the efficiency of a natural gas diesel engine, an engine control system is required to vary the amount of pilot fuel injected under various load/speed operating conditions.

The second problem area with natural gas dual-fuel engines is the loss of combustion control due to knock (Karim (1966)) as a result of auto-ignition of the natural gas under certain operating conditions. This is only a problem with very high compression ratios and highly turbocharged engines where the temperature of the inlet air flow mixture is very high. An engine control system is required to limit the knock under these severe operating conditions. If the natural gas is pure methane, this should be relatively simple to accomplish.

The third problem is how to introduce the natural gas into the engine in an efficient manner to produce a homogeneous, easily ignitable mixture.

For a four stroke engine this can most simply be done by the addition of a carburetor for metering the natural gas and air, while retaining the liquid injector to supply pilot diesel fuel to ignite the mixture (Alperstein (1958)). Throughout the load range of the engine the air fuel ratio is maintained at a constant value, resulting in a fairly homogeneous mixture throughout the combustion chamber. The engine power is varied by simply changing the throttle position which varies the mass of the air/natural gas mixture inducted into the engine.

## 5.4 Existing Dual-Fuel NGV Conversion Systems

Presently there are a number of commercially available four-stroke dual-fuel NGV diesel conversion systems. These systems are generally simple mechanical devices most of which do not employ electronic control systems to optimize the operating characteristics of the engine. What follows is a brief summary of currently available dual-fuel diesel NGV conversion systems.

### 1) Mogas Fuel Systems Inc.

This company imports the ASI dual-fuel conversion system from Italy. Three Caterpillar 3208 diesel engines have been converted using this system, and are presently operational. Mogas recently modified this system to operate on a Cummins 855 CID 350 BHP turbocharged diesel engine.

### 2) GeoSource Canada Inc.

This company has developed their own conversion system for a Cummins diesel engine. Their system features some electronic control, however, complete details on this system are not currently available.

3) Fiba Canning

This company has converted two vehicles to dual-fuel operation (Cummins engines) using a relatively straight forward mechanical control system.

4) B.C. Research

B.C. Research has developed a conversion system for 6.2 L General Motors diesel engine, operating in a GMC Suburban station wagon.

## 5.5 NGV/Diesel Conversion in New Zealand

The following is a summary of the current situation in New Zealand concerning the conversion of diesel engines to dual NGV/diesel operation:

1. Transport Fuel Systems (NZ) Ltd., Auckland.

   (a) The company has a commercial system and will quote a price for a job.

   (b) The system is not applicable to all types of diesel engines and the company will advise enquirers on the technical feasibility of using it in a particular situation.

   (c) Development work on the conversion system, especially the possible use of electronics for control rather than the current mechanical system, is continuing.

(d) The company has converted an ERF diesel (Cummins engine) used as a petrol tanker and a truck used to haul timber. Two Fiat V8s have been converted for the towing of semi trailers mounted with large tubes to carry NGV from mother stations to daughter stations.

(e) Current NGV replacement is between 30 and 40 percent.

2. Moller-Johnson Motors Limited, New Plymouth.

(a) The company has a commercial system and will quote a price for a job.

(b) The first NGV/diesel powered vehicle converted by the company, an Isuzu three tonne van powered by a four cylinder diesel, has now completed over 100,000 kilometers. It uses a fuel mixture of 70 percent NGV and 30 percent diesel. To date the engine appears to have suffered no detrimental effects. The vehicle had run 230,000 kilometers before conversion.

(c) The company has also converted Isuzu VPR 290 tractor units and a Dodge RG 13 tractor unit (turbocharged). The Dodge unit has a laden weight of 19 tonnes and a fuel mixture of 50:50 NGV/diesel.

(d) Recently a Daihatsu 3 tonne diesel-engined truck (2300 cc motor) has been successfully converted to high supplementation dual NGV/diesel operation. A switch in the cab enables the fuel supply to be changed from diesel to NGV/diesel with up to 80 percent supplementation.

3. The Welgas Holdings System.

   (a) This system has been developed by Welgas Holdings in conjuction with Tessari of Italy (joint venture).

   (b) The system is commercial and the company will quote for a job.

   (c) At least two truck engines have been converted using the system, with up to 80 percent replacement of diesel by NGV. A considerable number of diesel trucks in Pakistan have also been converted.

4. Diesel Injection Services, Lower Hutt.

   The conversion system being developed by this group is at the experimental/trial stage.

A group headed by Professor John Stephenson in the Mechanical Engineering Department of the University of Auckland, has been doing experimental work on NGV/diesel conversions under a Liquid Fuels Trust Board contract. The group's report on its work is at the draft stage.

## 6.0 CONTROL SYSTEM STRATEGY FOR A SECOND GENERATION DUAL-FUEL CONVERSION SYSTEM

In section 5 it was pointed out that there are a number of currently available NGV dual-fuel conversions that can be used with existing diesel engines used in heavy trucks. However it must be noted that these systems do not optimize the performance of the engine and the degree of substitution of diesel fuel is much smaller than the levels achieved in single cylinder research engines. In addition it has been reported

that some of these conversion systems allow the engine to operate in the knocking regime which could result in serious damage to the engine. Thus there is a requirement for a more advanced "second generation" dual-fuel conversion system.

The control system for any second generation 4-stroke diesel dual-fuel conversion system must meet the following criteria:

I) Improve the very low thermal efficiencies of dual-fuel engines when operated under part load conditions. There are five possible methods to accomplish this:

   (a) increase the amount of pilot fuel injected for decreasing load,

   (b) decrease the amount of air inducted into the engine through throttling of the air supply,

   (c) increase the intake charge temperature (eg. glow plugs, valve timing, exhaust heat circulation, etc.),

   (d) modify the fuel injection timing,

   (e) employ exhaust gas recirculation to heat and modify the composition of the incoming charge.

   A second generation conversion system could use any combination of the above as a function of load to increase the very low thermal efficiency at part load conditions.

II) Prevent knocking of the engine at full load. There are a number of possible methods to accomplish this including retarding the fuel injection timing and lowering the intake charge temperature.

The intention of the development project proposed for Phase II activities is to build to prototype stage a new dual-fuel conversion system featuring an advanced control system which will satisfy conditions I and II given above.

## 7.0 RECOMMENDATIONS FOR THE DEVELOPMENT OF A MODERN DUAL-FUEL CONVERSION SYSTEM

Based on the results of the market analysis conducted in Section 2 it is clear that there are two distinct types of diesel trucks that could be considered for conversion to dual-fuel operation. The first type (which primarily includes Group 6 and 7 vehicles) is composed of trucks exclusively confined to one major urban area. The second type (primarily Group 8 vehicles) is composed of trucks dedicated to inter-city routes.

Trucks of the first type are the most attractive for conversion to natural gas at the present time due to a number of factors given below:

- an urban truck can be refuelled at a central location or at public refuelling stations located in urban areas,
- the required natural gas cylinders do not generally impose any insurmountable weight or volume restrictions on the truck.

Trucks of the second type (inter-city) are not nearly as attractive for conversion due to the present lack of an adequate network of refuelling stations along the major highways and to serious weight and volume restrictions imposed by the natural gas storage tanks. In addition there would be considerable driver resistance to the use of NGV since the truck would have to be refuelled approximately every 350-400 km as opposed to typically 1500 km using diesel fuel.

Based on these factors urban trucks are the most attractive for conversion and the development of a modern conversion system (Phase II) should be conducted for an engine suitable for this group. In Section 2.2.3 it was pointed out that the Caterpillar 3208 is used in about 50% of the trucks in this group. Hence the development of a modern conversion system for this engine is the probable best choice for the most immediate commercialization of natural gas dual-fuel in heavy trucks.

The second type of vehicles, while not as attractive for conversion immediately, still offers significant potential for conversion. As pointed out earlier there are two engines, the Caterpillar 3406 and the Cummins NTC 400, which dominate this group. Hence a modern conversion system developed for either of these engines would be appropriate for a large segment of the inter-city heavy trucks.

## 8.0 CONCLUSIONS

From our analysis it is clear that there could be a significant market for conversion of heavy trucks (Groups 6, 7 and 8) to NGV in the lower mainland of B.C. and in southern Ontario. Obviously other markets exist in Canada and United States and overseas for such a conversion. The most attractive group of trucks for conversion are those Group 6 and 7 vehicles confined to a major urban center. Group 8 trucks are suitable for conversion only when a reasonable number of refuelling stations adjacent to the major highways are constructed.

A review of relevant technical information on dual-fuel diesel engines has shown that diesel engines can be operated satisfactorily on natural gas. Most NGV dual fuel engines have been used in stationary applications. Recently a number of NGV dual-fuel conversion systems have been developed for heavy truck engines. In general these systems are not at a high

level of technical sophistication and do not optimize the operation of the engine under the varying speed/load conditions encountered in a truck engine. Hence there is a requirement to develop an improved dual-fuel CNG conversion system that will optimize the performance of the engine under transient speed/load conditions. The activities of Phase II will be involved with the development of such a system.

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